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## Lepton flavour violation at high energies: The LHC and a Linear Collider

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**Summary.** — We discuss several manifestations of charged lepton flavour violation at high energies. Focusing on a supersymmetric type-I seesaw, considering constrained and semi-constrained supersymmetry breaking scenarios, we analyse different observables, both at the LHC and at a future Linear Collider. We further discuss how the synergy between low- and high-energy observables can shed some light on the underlying mechanism of lepton flavour violation.

PACS 14.60.St – Non-standard-model neutrinos.

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PACS 13.66.Hk – Production of non-standard model particles in  $e^+e^-$  interactions.

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### 1. – Motivation

The observation of neutrino oscillations has provided the first clear evidence of new physics beyond the Standard Model (SM). In the SM lepton flavour is strictly conserved; by themselves, neutrino oscillations signal the violation of neutral lepton flavour, and open the door to general scenarios where, in analogy to the quark sector, both neutral and charged lepton flavours are no longer conserved. Neutrino phenomena can be trivially accommodated by minimal extensions of the SM, where (Dirac) neutrino mass terms are put by hand, and flavour mixing in the leptonic sector is parametrised by the  $U_{\text{PMNS}}$  (the  $\text{SM}_{m_\nu}$ ). However, in the context of such a simple framework, the contributions to charged lepton flavour violation (cLFV) observables, such as  $\mu \rightarrow e\gamma$ , are expected to be very small, beyond any experimental reach. This implies that the observation of any cLFV manifestation would indisputably reveal the presence of New Physics (NP) other than the  $\text{SM}_{m_\nu}$ .

Among many appealing NP models accommodating neutrino data (for a brief overview see [1]), here we consider the hypothesis of a supersymmetric (SUSY) type I seesaw, which can open the door to a large number of cLFV observables at/below the TeV scale. These observables can be searched for in low-energy, high intensity facilities or in high-energy colliders as the LHC or a future Linear Collider (LC). We focus on the prospects of a SUSY seesaw concerning cLFV signals at high-energies: we first re-evaluate the prospects for observing cLFV observables at the LHC (such as new edges in dilepton mass distributions and flavoured slepton mass differences), and whether the type-I SUSY seesaw can still be probed via the synergy between high- and low-energy cLFV observables [2, 3]. We then address the potential of a Linear Collider regarding lepton flavour violation, in particular  $e\mu$ + missing energy final states, arising from  $e^+e^-$  and  $e^-e^-$  collisions [4]. We address the potential background from SM and SUSY charged currents, also exploring the possibility of electron and positron beam polarisation. We finally discuss a potential “golden channel” for cLFV at a LC:  $e^-e^- \rightarrow \mu^-\mu^- + E_{\text{miss}}$ .

## 2. – Theoretical framework: the SUSY seesaw

We consider a supersymmetric version of a type-I seesaw, where 3 right-handed (RH) neutrino superfields are added to the Minimal Supersymmetric SM (MSSM) particle content. In our analysis we assume a flavour-blind SUSY breaking mechanism where the soft breaking parameters satisfy universality conditions at some high-energy scale ( $M_{\text{GUT}} \sim 10^{16}$  GeV). We consider cases of strict universality, *i.e.* an embedding onto the constrained MSSM (cMSSM), as well as semi-constrained frameworks, where one breaks strict universality for squark, slepton and Higgs soft-breaking terms at  $M_{\text{GUT}}$  (but still preserving flavour universality), also assuming that gluino and electroweak (EW) gaugino masses are independent (for a detailed discussion, see [3]).

After EW symmetry breaking, the light neutrino masses are given by the seesaw relation,  $m_\nu \simeq -v_2^2 Y^\nu{}^T M_R^{-1} Y^\nu$  which in turn suggests a convenient parametrisation for the neutrino Yukawa couplings [5],  $Y^\nu v_2 = i \sqrt{M_R^{\text{diag}}} R \sqrt{m_\nu^{\text{diag}}} U_{\text{PMNS}}^\dagger$ , where  $v_2$  is one of the vacuum expectation values of the neutral Higgs,  $U_{\text{PMNS}}$  is the leptonic mixing matrix and  $R$  is a complex orthogonal matrix, parameterised in terms of three complex angles, that encodes additional mixings involving the RH neutrinos;  $m_\nu^{\text{diag}}$  and  $M_R^{\text{diag}}$  denote the (diagonal) light and heavy neutrino mass matrices.

In the SUSY seesaw, flavour mixing in the slepton sector is radiatively induced due to the non-trivial structure of the neutrino Yukawa couplings [6]. Even in the case of universal SUSY breaking terms, renormalisation-group running will give rise to flavour-violating entries in the slepton masses. The misalignment of flavour and physical slepton eigenstates leads to LFV neutral and charged lepton-slepton interactions, and will be manifest in contributions to numerous cLFV observables. Having posited a unique source of LFV ( $Y^\nu$ ) implies that all observables will exhibit a certain degree of correlation, which in turn might allow to indirectly probe the high-scale seesaw hypothesis.

At low-energies, virtual SUSY particles mediate rare transitions and decays. In our work, we mostly focus on radiative muon decays, whose recent bound from MEG is  $\text{BR}(\mu \rightarrow e\gamma) \lesssim 5.7 \times 10^{-13}$  [7].

High-energy colliders (such as the LHC or a future LC) provide direct access to the slepton sector; provided the centre of mass energy is sufficiently large, one can study on-shell sleptons, either directly produced (as in a LC), or then arising from decay chains of directly produced coloured states or EW-inos (as at the LHC). It is important to notice

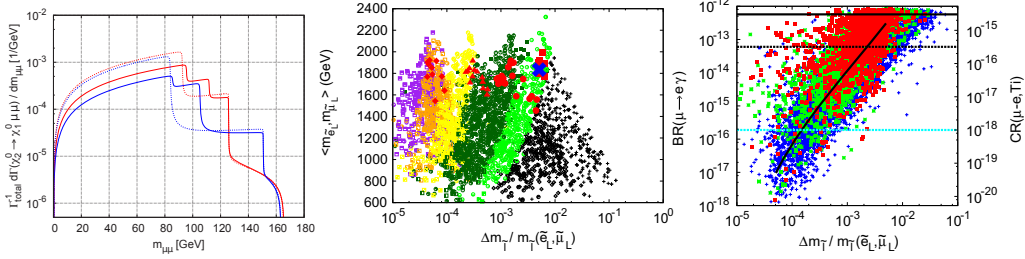


Fig. 1. – On the left, example of invariant dimuon mass distributions from  $\chi_2^0$  decays, for the cMSSM (dashed) and the SUSY seesaw (full lines), from [2]. Central panel: slepton mass splittings *vs.* average mass for a semi-constrained SUSY spectrum. We have taken  $R = 1$ , fixing the RH spectrum as  $M_{R_1} = 10^{10}$  GeV,  $M_{R_2} = 10^{11}$  GeV, and  $M_{R_3} = 10^{12-15}$  GeV. Colour code denotes regimes of  $\text{BR}(\mu \rightarrow e\gamma)$ : black points are already excluded, and light green are within MEG reach, from [3]. On the right,  $\text{BR}(\mu \rightarrow e\gamma)$  *vs.* slepton mass splittings. Horizontal lines denote current bounds and future sensitivity. The matrix  $R$  is randomly varied and the RH spectrum set as  $M_{R_1} = 10^{10}$  GeV,  $M_{R_2} = 10^{11}$  GeV, and  $M_{R_3} = 10^{13,14,15}$  GeV (blue, green and red points), from [3].

that LFV in charged current interactions (*e.g.*  $\chi^\pm - \tilde{\ell}_i - \nu_j$  interactions) can arise as a simple consequence of an ad-hoc implementation of leptonic mixing, and does not signal any new physics beyond the  $\text{SM}_{m_\nu}$  (in this case the  $\text{MSSM}_{m_\nu}$ ). On the other hand, LFV in neutral currents indisputably signals such new physics (*e.g.*, the type I SUSY seesaw).

In the following sections we illustrate some cases of cLFV at high-energies, mostly focusing on flavour violation in the (s)electron-(s)muon sector<sup>(1)</sup>.

### 3. – cLFV at the LHC

To illustrate cLFV observables at the LHC, we consider slepton production from wino-like neutralino decays. The shape of the dilepton mass distribution from  $\chi_2^0 \rightarrow \tilde{\ell}\ell \rightarrow \ell\ell\chi_1^0$  decays allows to extract information on the slepton spectrum; in particular, the position of the edges allows to determine the slepton mass, while the number of edges translates the different number of sleptons participating in the decay.

In the cMSSM (*i.e.*, in the absence of a seesaw mechanism),  $\chi_2^0$  decays lead to identical flavour, opposite-sign, final state leptons. The dielectron and dimuon invariant mass distributions ( $m_{ee}$  and  $m_{\mu\mu}$ ) have a double triangular shape, each exhibiting two edges, which correspond to the exchange of the left- and right-handed selectron or smuon. This is illustrated by the dashed lines on the left pannel of fig. 1, for two cMSSM benchmark points (for details, see [2]). A comparison of  $m_{ee}$  and  $m_{\mu\mu}$  would reveal that the edges are superimposed, implying that sleptons of the first two families are degenerate in mass (to a very good approximation):  $m_{\tilde{e}_L(\tilde{e}_R)} \approx m_{\tilde{\mu}_L(\tilde{\mu}_R)}$ . Should a type-I SUSY seesaw be at work, then several differences would be manifest in the dilepton mass distributions. Firstly, and as can be seen from inspection of the full lines of the left panel of fig. 1, a new edge appears, corresponding to the presence of an additional state in the  $\chi_2^0 \rightarrow \mu\mu\chi_1^0$  decays—other than intermediate left- and right-handed smuons, a stau

<sup>(1)</sup> For a discussion of flavour violating final states with a  $\tau$  lepton, in particular  $\mu\tau + E_{\text{miss}}^T$ , see M. E. Gómez, these proceedings.

( $\tilde{\tau}_2$ ) also contributes,  $\chi_2^0 \rightarrow \tilde{\tau}_2 \mu \rightarrow \mu \mu \chi_1^0$ . This provides an indisputable *signal of cLFV at the LHC*. Secondly, when comparing  $m_{ee}$  and  $m_{\mu\mu}$ , the edges corresponding to the left-handed (LH) sleptons are no longer superimposed, which implies that left-handed sleptons of the first two families are no longer degenerate, in other words, there will be a non-negligible flavour violating slepton mass splitting, parametrised as

$$(1) \quad \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) = \frac{|m_{\tilde{e}_L} - m_{\tilde{\mu}_L}|}{\langle m_{\tilde{e}_L}, m_{\tilde{\mu}_L} \rangle}.$$

We now proceed to discuss the prospects for studying this observable (and its synergy with low-energy cLFV observables) at the LHC, following the most recent experimental results (in particular LHC SUSY negative searches and the measurement of the Higgs mass,  $m_h$ , the recent MEG bound on  $\mu \rightarrow e\gamma$  decays, and the determination of  $\theta_{13}$ ) [3]. Our analysis has shown that in the framework of a type-I seesaw embedded in the fully constrained SUSY models, LHC data (in particular the measurement of  $m_h$ ) precludes the possibility of simultaneously having  $\text{BR}(\mu \rightarrow e\gamma)$  within MEG reach and sizeable slepton mass differences associated with a slepton spectrum sufficiently light to be produced. On the other hand, considering semi-constrained scenarios allows to circumvent some of the strongest LHC bounds, especially on  $m_h$ , allowing for non-negligible slepton mass splittings (for a comparatively light slepton spectrum). Depending on the SUSY regime, one can still have  $\Delta m_{\tilde{\ell}} \sim 0.1\% - 1\%$ , for  $m_{\tilde{\ell}}$  ranging from 800 GeV to 1.6 TeV. This is illustrated on the central panel of fig. 1, which also reveals that the associated rates for low-energy cLFV observables, such as  $\text{BR}(\mu \rightarrow e\gamma)$  and  $\text{CR}(\mu - e, \text{Ti})$  are also within experimental reach.

Finally, the potential measurement of low- and high-energy cLFV observables allows to probe the type-I SUSY seesaw hypothesis (for a type-III SUSY seesaw, see [8]): as shown on the right panel of fig. 1, these observables exhibit a strong degree of correlation, even when fully exploring the degrees of freedom of the neutrino Yukawa couplings (see parametrisation of  $Y^\nu$  given in sect. 2). Any measurement  $\Delta m_{\tilde{\ell}} \gtrsim \mathcal{O}(1\%)$  must be accompanied by the observation of  $\mu \rightarrow e\gamma$  at MEG to substantiate the SUSY seesaw hypothesis; on the other hand, isolated manifestation of either low- or high-energy cLFV would strongly suggest that sources of LFV, other than—or in addition to—the SUSY seesaw would be present.

#### 4. – cLFV at a Linear Collider

If SUSY is realised in Nature, Linear Colliders are ideal laboratories to study the slepton sector, offering a perfect environment for high-energy precision studies such as cLFV in slepton production and decays. The comparatively clean environment (due to a reduced QCD activity), associated to the high-efficiency of the muon and electron detectors implies that cLFV observables can be measured to a very good precision; beam polarisation allows to reduce the SM backgrounds and probe the chirality structure of the new processes, and the possibility of having an  $e^-e^-$  beam option offers a powerful tool to further probe the properties of the new states. Provided that the centre of mass energy is sufficiently high, one can have direct slepton production, and study slepton phenomena in short(er) SUSY decay chains.

In addition to the observables already considered in the previous section devoted to the LHC (*i.e.* edges in dilepton mass distributions, slepton mass splittings), there are many other cLFV phenomena that can be probed at a LC. Here we focus on

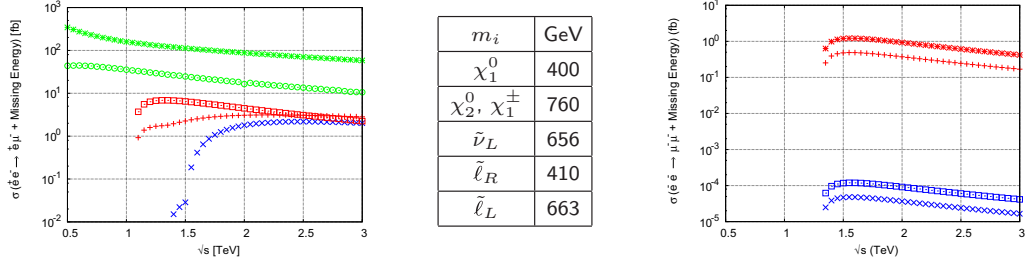


Fig. 2. – On the left,  $\sigma(e^+e^- \rightarrow e^+\mu^- + E_{\text{miss}}^T)$ , with  $E_{\text{miss}}^T = 2\chi_1^0$  (signal, red),  $2\chi_1^0 + (2, 4)\nu$  (SUSY background, blue) and  $(2, 4)\nu$  (SM background, green), as a function of the centre-of-mass energy,  $\sqrt{s}$ . We fix  $M_R = 10^{12}$  GeV, for a SUSY spectrum summarised by the table above, showing the results for both unpolarised (crosses, times and asterisks) and fully polarised beams (squares and circles). On the right,  $\sigma(e^-e^- \rightarrow \mu^-\mu^- + E_{\text{miss}}^T)$ , for the same SUSY seesaw choice, also in the unpolarised and fully polarised case. From [4].

$e^\pm e^- \rightarrow e^\pm \mu^- + E_{\text{miss}}$ , where the missing energy can be in the form of lightest neutralinos (cLFV signal), neutralinos and neutrinos (corresponding to the SUSY charged current background - flavour violating vertices due to the presence of the  $U_{\text{PMNS}}$ ) and neutrinos (SM background, again due to  $U_{\text{PMNS}}$  flavour mixing in charged currents). We will also discuss the potential for cLFV of  $e^-e^- \rightarrow \mu^-\mu^- + E_{\text{miss}}$ . A detailed discussion of the different processes and observables can be found in [4].

**4.1.  $e^+e^-$  beam option.** – We begin with an illustration of the potential of  $e^+e^-$  beam option for cLFV: on the left panel of fig. 2 we display the cross section of different processes contributing to  $e^+e^- \rightarrow e^+\mu^- + E_{\text{miss}}$ . We consider a sample benchmark point, with conservative SUSY seesaw assumptions (*i.e.*,  $R = 1$ , with all FV arising from the  $U_{\text{PMNS}}$ , and an intermediate RH neutrino scale,  $M_R \sim 10^{12}$  GeV). Relevant information on the neutralino and slepton spectra is also summarised in fig. 2.

Although the  $\text{SM}_{m_\nu}$  background clearly dominates, it is expected to be easily disentangled from SUSY events via appropriate cuts. Provided that  $\sqrt{s}$  is above the slepton production threshold, the cLFV signal dominates the  $\text{MSSM}_{m_\nu}$  background. The left panel of fig. 2 also conveys the potential of beam polarisation: to fully reveal it, we considered an ideal scenario where both beams are fully polarised. As can be seen, polarising the beams reduces the  $\text{SM}_{m_\nu}$  background and essentially removes the SUSY one.

**4.2.  $e^-e^-$  beam option.** – In the absence of doubly charged particles (as is the case of the SUSY seesaw), all slepton production in  $e^-e^-$  collisions occurs via  $t$ -channel neutralino exchange. Having similar slepton production for signal and SUSY background implies that polarising the beams will have a smaller effect.

As mentioned before, the  $e^-e^-$  beam option is ideal for what might be a truly “golden channel” of cLFV at a LC:  $e^-e^- \rightarrow \mu^-\mu^- + E_{\text{miss}}$ . When compared to other signals of cLFV at a LC already discussed—*e.g.*  $e^\pm e^- \rightarrow e^\pm \mu^- + E_{\text{miss}}^T$ —the SM model background is extremely tiny in this case. SUSY background processes are still present, but are subdominant when compared to the signal, as the corresponding cross sections differ by at least one order of magnitude. This is illustrated in the right panel of fig. 2, for the same points previously considered. Notice that the signal clearly dominates (by about four orders of magnitude) the SUSY background.

Provided that the c.o.m. energy is sufficiently large (above the slepton production threshold),  $e^-e^- \rightarrow \mu^-\mu^- + E_{\text{miss}}^T$  is an ideal cLFV discovery channel, allowing the identification of a new physics scenario, such as the SUSY seesaw—always under the assumption of having a unique source of Lepton Flavour Violation present. Naturally, one would be also confirming the Majorana nature of the exchanged particles in the  $t$ -channel. Moreover, right-polarising both beams would allow to test the seesaw hypothesis since, in such a framework, slepton cLFV is predominantly a left-sector phenomenon.

Although not discussed here, one can also study the synergy between low-energy cLFV observables and high-energy ones measured at a LC (similar to the LHC) [4]. In addition to probing the hypothesis of a type I SUSY seesaw, such a study can also hint towards the seesaw scale.

## 5. – Outlook

Lepton flavour violation observables play a leading rôle in unveiling the presence of NP. Here we have discussed the potential of high-energy colliders (LHC and a future LC) for the study of cLFV signals. As an example, we have considered the appealing case of a type-I SUSY seesaw.

At the LHC, the most striking cLFV signal would be the appearance of multiple edges in dimuon mass distributions from EW-ino decays. We have also considered the prospects for observing flavoured slepton mass differences (and exploring their synergy with low-energy cLFV observables) finding that semi-constrained SUSY scenarios still offer promising prospects for these studies.

We have revisited the case for cLFV at a Linear Collider, exploring both beam options and beam polarisation, further discussing the relevant backgrounds for charged current processes. Provided that the c.o.m. energy is above the slepton production threshold, one can indeed expect abundant events (even prior to selection cuts). We have also pointed a possibly “golden channel” for cLFV,  $e^-e^- \rightarrow \mu^-\mu^- + E_{\text{miss}}$ , one of the cleanest experimental setups to probe both cLFV and lepton number violation.

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